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14. ABSTRACT
This project was a 1-year supplement (plus 1-year no-cost extension) to continue analysis and publication of results obtained during the "Scalable Lateral Mixing and Coherent Turbulence" (a.k.a., LatMix) DRI. The initial effort was a collaboration between M. Sundermeyer (UMass Dartmouth), J. Ledwell and E. Terray (WHOI), and B. Concannon (NAVAIR), and included airborne lidar operations as well as a substantial part of the LatMix field operations and analysis. The primary objective of present effort was to complete the analysis and write-up of additional manuscripts relating to LatMix, and to further strengthen the results for multiple manuscripts already published or submitted for publication.

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-- FINAL REPORT –

LatMix 2011 and 2012 Dispersion Analysis

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MAJOR GOALS

Our long-term goal is to better understand lateral mixing processes in the ocean on scales of 10 m to 10 km, i.e., the "submesoscale, and to understand the underlying mechanisms and forcing, as well as the temporal, spatial, and scale variability of such mixing. This research contributes to fundamental knowledge of ocean dynamics at these scales, and to efforts to parameterize sub-grid scale mixing and stirring in numerical models. Our research also enhances modeling and understanding of upper ocean ecosystems, since the flow of nutrients and plankton depends on stirring and mixing at these scales.

This project was a 1-year supplement (plus 1-year no-cost extension) to continue analysis and publication of results obtained during the "Scalable Lateral Mixing and Coherent Turbulence" (a.k.a., LatMix) DRI. The initial effort was a collaboration between M. Sundermeyer (UMass Dartmouth), J. Ledwell and E. Terray (WHOI), and B. Concannon (NAVAIR), and was performed jointly with a collaborative NSF grant to M. Sundermeyer, J. Ledwell, and E. Terray (see "Related Projects" below). ONR support included the airborne lidar operations as well as a substantial part of the field operations and analysis.

A primary objective of our LatMix work was to directly measure rates of submesoscale lateral dispersion in the upper ocean and pycnocline using dye and drogued drifter release studies. Within this, we sought to determine the extent to which shear dispersion – the interaction of vertical mixing with vertical shear – can explain lateral dispersion at scales of 10 m to 10 km. Additionally, we sought to determine whether slow but persistent vortical motions enhance the stirring attributable to shear dispersion. Throughout this work, we also shared the overall objectives of the Lateral Mixing DRI to determine the extent to which submesoscale stirring is driven by a cascade of energy down (in wavelength) from the mesoscale, versus a propagation of energy upwards from small mixing events (e.g., via generation of vortices). A key technical goal of our work was to develop the use of airborne light detection and ranging (lidar) surveys of evolving dye experiments as a tool for studying submesoscale lateral dispersion.

Numerous papers by our group relating to the LatMix field and modeling efforts are either published, submitted, or nearing completion (see list of references). Our primary analyses of the LatMix dye and

drogued drifter studies have contributed significant insight into the underlying mechanisms responsible for isopycnal and diapycnal mixing and cross-frontal transport during both the 2011 and 2012 field campaigns. Beyond the manuscripts already published on these results, however, there have also been numerous additional aspects of the data and analysis that we believe represent significant contributions, and hence also warrant publication. These include our inversion approach for determining absolution dye concentration from raw waveforms collected during the LatMix 2011 airborne lidar surveys, and completion of the analysis and write-up of major results stemming from the LatMix 2012 dye release experiments. Publication of additional manuscripts on these topics, as well as ancillary analysis associated with this effort, has the potential to significantly enhance the impact of the LatMix field efforts, and further strengthen the results of multiple manuscripts already published or in preparation by our group as well as other LatMix PIs.

ACCOMPLISHED

1) Major Activities

Our approach during the primary LatMix field effort was to release dye patches on an isopycnal surface in the seasonal pycnocline, and along the Gulf Stream front, and to survey their evolution for periods of 1 to 6 days, in collaboration with other DRI investigators. Two major field experiments were conducted under LatMix, one 21-day experiment in the Sargasso Sea in June 2011, and one 25-day experiment along the north wall of the Gulf Stream in Feb/Mar 2012. Both efforts were multi-ship, multi-investigator efforts, of which the dye, drifter, and lidar work were one part. Analysis of data from these field efforts has been a collaborative effort between the field PIs, numerical modelers, and theoreticians, and has resulted in multiple multi-investigator manuscripts published or submitted for publication.

2) Specific Objectives

The primary objective of present effort was to complete the analysis and write-up of additional manuscripts relating to the LatMix 2011 and 2012 field experiments, and to further strengthen the results for multiple manuscripts already in preparation. The following activities have been performed under this project:

- Completion of one publication addressing observations / theoretical considerations of intermittency and log-normality of diapycnal mixing as affects vertical shear dispersion (Kunze and Sundermeyer, 2015).
- Completion of one publication addressing exchange of water along the north wall of the Gulf Stream (Klymak et al, 2016).
- Additional analysis and write-up of a manuscript describing the primary rhodamine dye release experiments conducted during LatMix 2011 (Sundermeyer et al., in prep(a)), and a second manuscript addressing the shear dispersion null hypothesis (Birch et al., in prep).
- Additional analysis and write-up of a manuscript plus multiple conference presentations describing the primary rhodamine dye release experiments conducted during LatMix 2012 (Sundermeyer et al., in prep(b)).

3) Significant Results

Regarding the first bullet above, we have published a theoretical paper re-examining the null hypothesis of internal wave shear dispersion (Kunze and Sundermeyer, 2015). Our analysis suggests that, taking into account (i) the intermittency of shear-driven turbulence, (ii) its lognormality, and (iii) its correlation with unstable finescale near-inertial shear, internal-wave shear dispersion cannot necessarily be discounted as a significant contributor to lateral dispersion on the open ocean. This suggests that, considering infrequent occurrence of turbulence bursts and the possible correlation between diapycnal diffusivity Kz and the off-diagonal vertical strain, there may be no need to invoke additional submesoscale mixing mechanisms such as vortical-mode stirring or internal-wave Stokes drift to explain previously reported discrepancies. Additional theoretical, numerical, and/or observational analysis will be required to confirm this result.

Regarding the second bullet above, analysis of the 2012 LatMix hydrography, velocity, and dye along the north wall of the Gulf Stream reveals a mechanism by which significant amounts of Gulf Stream water (order 0.25 Sverdrups) are detrained via streamers that peel off and are carried away by cooler fresher water to the north. Analysis shows that along isopycnals, the Gulf Stream front has a sharp compensated temperature-salinity contrast, with distinct mixed water between the two water masses 2 and 4 km wide. This mixed water does not increase downstream despite substantial energy available for mixing. Instead, a series of streamers detrain this water at the crest of meanders, while subpolar water replaces the mixed water and resharpens the front. The water mass exchange accounts for a northward flux of salt of 0.5–2.5 psu m^2/s, (large-scale diffusivity O (100 m^2/s)). This is similar to bulk-scale flux estimates of 1.2 psu m^2/s and supplies fresher water to the Gulf Stream required for the production of 18 deg subtropical mode water.

Regarding the third bullet above, we have conducted a re-analysis of the LatMix 2011 dye data collected from the UMass Acrobat system, as well as the Oregon State University MVP tow package. Revised diapycnal and isopycnal diffusivities are consistent with previous estimates of $Kz = 5 \times 10^{-6}$ m^2/s for the first experiment (low strain), and $Kz = 3\text{-}6 \times 10^{-6}$ m^2/s for the second (intermediate strain); and $Kh = 0.5 - 4$ m^2/s for both experiments, but now with additional quality control and data processing metrics enabling better confidence intervals. With this re-analysis, we are in the final stages of submitting this primary publication stemming from the LatMix 2011 dye studies (draft manuscript available at PI's website). In addition, we are finalizing the campanion manuscript relating to the LatMix 2011 dye studies describing the null hypothesis of shear dispersion (draft manuscript also available at PI's website).

Regarding the fourth bullet above, we have similarly made considerable progress on the LatMix 2012 dye data analysis, including presenting our primary results at both the 2016 Ocean Sciences meeting in New Orleans, and the Amerimech Symposium in Woods Hole. Key findings include lower-bound diffusivities at scales of O(1-10) km inferred from dye of $Kz = 10\text{-}70$ cm^2/s, and $K_h = 10\text{-}50$ m^2/s. Considering the two symmetric instability dye releases, we also found that in one case the dye mixed from the near surface (28 m) to denser, deeper water, becoming colder and fresher (suggesting mixing primarily with cooler fresher water to the north of the Gulf Stream); while in the second case it mixed from the near surface (26 m) to denser, deeper water, becoming colder and saltier (suggesting mixing primarily with cooler saltier water at depth beneath the Gulf Stream). The dye released at 120 m depth along the north wall showed different behavior, mixing rapidly down from 120 to 180 m within 1 day, indicating either rapid downwelling, or a diapcynal mixing rate of O(100) cm^2/s. Last, the dye released at 55 m along the north wall of the Gulf Stream was within a cooler fresher filament that was enveloped by warmer, saltier water associated with a north wall streamer, and subsequently mixed

and/or advected rapidly toward the surface (within 1 day), warming and becoming more saline along the way. Results from the two north wall dye experiments have been incorporated into Klymak et al, (2016). The remaining results from the 2012 dye experiments are being finalized as part of a stand-alone LatMix 2012 dye manuscript (Sundermeyer et al, in prep(b)), which will provide a detailed description of the four dye experiments, including the mixing, transport and fate of the patches.

4) Key Outcomes / Other Achievements

Completion of two published manuscripts: Kunze and Sundermeyer (2015), and Klymak et al. (2016). Multiple LatMix-related conference presentations (see Products, below).

TRAINING

Nothing to report.

DISSEMINATION

Multiple peer-reviewed publications. Multiple conference presentations and institutional seminar. Also presented series of lectures/laboratory demonstrations at Sandwich Massachusetts Public School system's "Exploration & Discovery Day," including discussing careers in physical oceanography, and lab/rotating table demonstrations to approximately 60 seventh and eighth grade students.

PLANS

Nothing to report.

RELATED PROJECTS

The above work and findings follow on a joint effort on the part of LatMix DRI PIs Ledwell and Terray (WHOI) and Sundermeyer (UMass Dartmouth) under ONR grants N00014-09-1-0175 and N00014-09-1-0194, respectively, and Brian Concannon (NAVAIR) under ONR award N0001411WX21010. Furthermore, this work was coordinated with the other projects of the Lateral Mixing DRI.

Field instrumentation used in the 2011 field work was purchased in part under DURIP grant N00014-09-1-0825, and in part under a related NSF project entitled "Collaborative Research: LIDAR Studies of Lateral Dispersion in the Seasonal Pycnocline", NSF Awards OCE-0751734 (UMass) and OCE-0751653 (WHOI). The PIs efforts under the ONR LatMix DRI were performed in coordination with the PIs efforts under NSF Awards OCE-0751734 (UMass) and OCE-0751653 (WHOI).

PARTICIPANTS

Miles A. Sundermeyer

STUDENTS

None.

PRODUCTS

Websites:

http://www.smast.umassd.edu/mixing/lidar_ONR_NSF.php

Conference Presentations:

Sundermeyer, M. A.; D.A. Birch, C. Lee, J.M. Klymak, E. D'Asaro, R.K. Shearman, L.N. Thomas; Observations of Dye Dispersion in the Gulf Stream Core and North Wall (Paper No. PO21A-05). AGU/ASLO Ocean Sciences Meeting, February, 2016, New Orleans, LA.

Early, J. J., M.-P. LeLong, K.S. Smith, **M.A. Sundermeyer**, A.M. Sykulski; Disentangling Mesoscale Strain and Internal Waves Using Surface Drifters (Paper No. PO41B-03). AGU/ASLO Ocean Sciences Meeting, February, 2016, New Orleans, LA.

Sundermeyer, M. A.; D.A. Birch, C. Lee, J.M. Klymak, E. D'Asaro, R.K. Shearman, L.N. Thomas; Observations of Dye Dispersion in the Gulf Stream Core and Across the North Wall. AmeriMech Symposium on Fluid Transport and Nonlinear Dynamics; Woods Hole, MA, May, 2016.

Sanchez-Rios, A, R.K. Shearman, J.M. Klymak, C. Lee, E. D'Asaro, **M. A. Sundermeyer**, J. Gula, S. Pierce; Submesoscale Features at the Gulf Stream North Wall and their Impact on the Heat and Salt Transport During the LatMix Survey Winter 2012. 2016 Liège Colloquium, Submesoscale Processes: Mechanisms, Implications and New Frontiers; Liège, Belgium, May 2016.

Sundermeyer, M. A., E. Kunze, D. A. Birch, J. R. Ledwell; Lateral Diffusivity Inferred from Dye: Revisiting the Shear Dispersion Hypothesis. Mid-Atlantic Bight Physical Oceanography and Meteorology Meeting; Fall River, MA, Oct, 2016.

Peer-Reviewed Publications:

Birch, D.A., ***M.A. Sundermeyer***, J.R. Ledwell, E.D'Asaro. A test of vertical shear dispersion in the ocean. [to be submitted, refereed]

Klymak, J.M., R.K. Shearman, J. Gula, C.Lee, E.A. D'Asaro, L.N. Thomas, R.R. Harcourt, A.Y. Shcherbina, ***M.A. Sundermeyer***, M.J. Molemaker, J.C. McWilliams, 2016. Submesoscale streamers exchange water on the North Wall of the Gulf Stream. *Geophys. Res. Lett.,* 43, 1226–1233, doi:10.1002/2015GL067152. [published, refereed]

Kunze, E., and ***M. A. Sundermeyer***, 2015. The Role of Intermittency in Internal-Wave Shear Dispersion. *J. Phys. Oceanogr.*, 45, 2979-2990, doi: 10.1175/JPO-D-14-0134.1 [published, refereed]

Sundermeyer, M.A., D.A. Birch, J.R. Ledwell. Dispersion studies in the Gulf Stream during winter forcing conditions. [to be submitted, refereed]

Sundermeyer, M.A., D.A. Birch, J.R. Ledwell, M.D. Levine, S.D. Pierce, B.T. Kuebel-Cervantes, B. Concannon. Dye Dispersion in the Open Ocean Seasonal Pycnocline at Scales of 1-10 km and 1-6 days. [to be submitted, refereed]